THE APPLICATION OF INTERMITTENT DETONATIVE COMBUSTION TO JET PROPULSION

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to

JET PROPULSION

by

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(1939)

SUBMITTED IN PARTIAL FULFILLMENT OF THE

REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
(1949)

Thesis
478

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May 20, 1949

Professor Joseph S. Newall
Secretary of the Faculty
Massachusetts Institute of Technolgy
Cambridge, Massachusetts

Dear Professor Newall:

I take pleasure in submitting herewith a thesis entitled "Intermittent Detonative Combustion applied to Jet Propulsion", in partial fulfillment of the requirements for the degree of Master of Science in Aeronautical Engineering.

Respectfully,

ACKNOWLEDGEMENTS

The author wishes to express his appreciation for advice and assistance rendered by Professor E.S. Taylor, Professor W.R. Hawthorne, and Professor J.H. Newell, who all helped him to an understanding of basic principles. Acknowledgement is also due to Mr. D.G. Luss, civilian engineer at the Naval Air Material Center, Philadelphia, Pennsylvania, who made available to the author the Volkenrode Translation, report No. L.F. 67, of the work of Hoffman in this field.

Particular gratitude and appreciation are due Mr. George Bemis, 232 Highland Street, Milton, Massachusetts, who gave the author free and unstinting use of his machine shop and advice in shop practice, and supplied him with materials gratis.

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1. INTRODUCTION

1.1 Statement of the Problem.

The need for increased power output and improved fuel economy in thermal jets has led to the use of higher pressure ratios and turbine inlet temperatures, with consequent multiplication of the problems of compressor and turbine design and reduced reliability and endurance. Attempts to minimize or eliminate these problems by use of pulsejets and ramjets have not met with marked success for well known reasons.

Detonative combustion offers an attractive solution to the problems involved in producing high pressure ratios and tolerating high temperatures. Detonative combustion may be considered to be a process in which combustion takes place within the high pressure area of a compression shock; in consequence, no mechanical compressor nor turbine are required, and as will be shown later, valves are also unnecessary.

It is the purpose of this paper to describe a thermal jet based on intermittent detonative combustion already developed; to attempt an analysis of the process involved; and to report the results of experiments conducted by the author in connection therewith.

1.2 Historical Background.

The phenomenon of detonation was discovered in 1881 by Berthelot and Vieille as well as by Mallard and Le Chatelier, who made detailed studies of the subject. Many subsequent investigations were made by Dixon and his students. The theoretical explanation of detonation was made by Chapman and Jouguet, following Becker's analysis of the compression shock. The pre-detonation period received particular attention from Sokolik and Shtshelkin, while Langweiler expressed the relation between detonation pressure and temperature and the pressure and temperature attained by combustion at constant volume. Recently, a detailed analysis has been made by Shapiro, Hawthorne, and Edelman (reference 1).

H. Hoffman, of the Deutsche Forschungsanstalt fur Segelflug (German Gliding Research Station) has been concerned since the spring of 1938 with the problem of developing a thermal jet operating on the principle of intermittent detonative combustion, and in a report dated November 10, 1939 described tests of a successful device (reference 2).

2. THE HOFFMAN APPARATUS

2.1 Description.

Fig. 1 shows a diagrammatic sketch of the intermittent detonative combustion apparatus developed by Hoffman (Fig. 28, reference 2). Essentially, the apparatus consists of a straight cylindrical tube closed at one end and provided with a spark-plug or other means of providing continuous ignition at the other, to which is attached a conical diffuser. Fuel and oxidizer are admitted through separate lines at the closed end of the combustion chamber in such a manner as to provide good mixing and turbulence.

The dimensions of the particular test apparatus to which reference will be made are as follows:

Length of combustion chamber......................	40.0 cm.
Diameter of combustion chamber....................	5.8 cm.
Length of diffuser................................	200.0 cm.
Diffuser half-angle of divergence.................	4.0 deg.

2.2 Operation.

The device described above operates on an intermittent cycle as follows. The combustible mixture flows toward the open end until it is ignited at the spark-plug. The flame front travels back toward the closed end, passing from ordinary combustion into detonation, and the detonation wave continues on to the baffle at the closed end where its reflection imparts a high impulse to the baffle. The pressure rise following the detonation wave imposes a temporary restriction on the flow

[illegible]

2. [illegible]

2.1 Description.

Fig. 1 shows a diagrammatic sketch of the intermittent [illegible]

[illegible]

The dimensions of the particular test apparatus to which reference will be made are as follows:

Length of combustion chamber	[illegible]
Diameter of combustion chamber	[illegible]
Length of tailpipe	[illegible]
Tailpipe half-angle of divergence	[illegible]

2.2 Operation.

[illegible]

of fresh fuel and oxidizer, extinguishing the flame. After the pressure falls fresh mixture again enters the combustion chamber and the cycle is repeated.

2.3 Results.

Using the apparatus above, Hoffman ran a series of tests to determine performance (Table 5, reference 2). The best results obtained are tabulated as follows:

Oxygen flow rate..........................	13.2 gm./sec.
Gasoline flow rate........................	3.9 gm./sec.
Total flow rate...........................	17.1 gm./sec.
Percent theoretical fuel..................	1[illegible]2.[illegible] %
Thrust....................................	8,4[illegible] gm.
Specific thrust...........................	491.[illegible] sec.
Specific fuel consumption.................	1.67 hr.
Theoretical specific thrust...............	497.[illegible] sec.

2.4 Discussion.

The foregoing results present three items of particular interest. First, attention is invited to the relatively high value of specific thrust obtained. This value is of the order of the specific thrust obtainable in rockets, but it should be remembered that in this device the combustible mixture is admitted under only such pressure as is necessary to insure the rate of flow desired, amounting in no case to more than a few pounds above atmospheric, whereas in a rocket the mixture must be admitted at combustion chamber pressure, amounting to several atmospheres of pressure.

The second point of interest is the value of specific fuel consumption. This is rather high, but follows from the fact that oxygen rather than air is the oxidizer, with the consequence that the mass accelerated per pound of fuel burned is reduced. Although the detonation velocity of air-fuel mixtures is lower than that of oxygen-fuel mixtures (reference 3), the net effect of using air instead of oxygen, provided the mixture can be caused to detonate, should serve to improve specific fuel consumption.

of fresh fuel and oxidizer, extinguishing the flame. After the pressure falls fresh mixture again enters the combustion chamber and the cycle is repeated.

4.3 Results.

Using the apparatus above, Phillips ran a series of tests to determine performance (Table 4, reference 4). The best results obtained are tabulated as follows:

Oxygen flow rate	17.0 gm./sec.
Gasoline flow rate	2.9 gm./sec.
Total flow rate	19.9 gm./sec.
Percent theoretical fuel	[illegible] %
Thrust	[illegible] gm.
Specific impulse	[illegible] sec.
Specific fuel consumption	[illegible] hr.
Theoretical specific impulse	[illegible] sec.

4.4 Discussion

The foregoing results, typical of those found of pulsating intermittent firing, attention is invited to the relatively high value of specific impulse obtained. This value is of the order of the specific impulse obtainable in rockets, but it should be remembered that in this device the combustible mixture is admitted under only such pressure as is necessary to insure the rate of flow desired, amounting in no case to more than a few pounds above atmospheric, whereas in a rocket the mixture must be admitted at combustion chamber pressure, amounting to several atmospheres of pressure.

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The final point of interest is a comparison of specific thrust with theoretical specific thrust based on the enthalpy of combustion of the fuel used. It will be noted that experimental specific thrust is appreciably higher than the theoretical maximum! This result is a consequence of the fact that the apparatus operates on an intermittent cycle, so that a new mass of air enters the diffusor and is accelerated once during each cycle. Since the process does not represent a steady-state condition initial acceleration must be taken into account, and calculations based entirely on the mass of mixture involved in the combustion process will be misleading.

3. ANALYSIS

3.1 Introduction.

The analysis of an intermittent detonative combustion device presents many difficulties. Foremost among these is the problem of flow in the diffusor. During each cycle pressure and velocity in the diffusor build up to a maximum in which the pressure is many times atmospheric and the velocity many times the velocity of sound. After combustion is completed both pressure and velocity drop rapidly, and due to inertia effects the pressure drops below atmospheric, followed by back-flow in the diffusor. Such back-flow represents a loss of momentum of which account must be taken.

Another equally important problem is the determination of the point in the combustion process where detonation sets in. Such information is necessary in order to determine how much of the charge surrenders its chemical energy in ordinary combustion and how much in detonative combustion. While the length of the pre-detonation path has been determined for stagnant mixtures (reference 3), no such determination has been made for turbulent mixtures.

The pressure, temperature, and detonation velocity at the beginning of detonation are also of interest. Jost (reference 3) and Lewis and von Elbe (reference 4) state that at the moment of origin detonation pressures are essentially higher and can be up to twice as high as the pressure in the stationary wave. Moreover, such abnormally high pressures persist for appreciable distances. Unfortunately, however, there appears to be no information about the law governing decay of initial pressure to steady-state pressure.

In view of the foregoing problems, the analysis following is divided into two parts. In the first part, the problem is treated as one of steady flow; and in the second part certain gross approximations are made in order to eliminate some of the unknowns discussed above. In both cases the analysis follows the methods of Shapiro, Hawthorne, and Edelman (reference 1), and calculations are based on the tables presented by these authors.

3.2 Symbols.

In general, the same symbols will be sued as those used by Shapiro, Hawthorne, and Edelman. Those pertinent, together with such additional symbols as necessary or minor changes, are listed below. Dimensions are in the foot-pound-second system. Attention is invited to the general rule that upper case letters are used wherever possible in order to reserve lower case letters for purposes of identification.

A..........cross-sectional area.
C..........speed of sound.
Cp.........specific heat at constant pressure.
Cv.........specific heat at constant volume.
D..........diameter.
F..........thrust.
H..........specific enthalpy.
K..........ratio of specific heats.
L..........length of duct.
M..........Mach number
N..........number of mols.
P..........pressure.
R..........gas constant.
T..........absolute temperature.

The pressure, temperature, and detonation velocity at the beginning of detonation are also of interest. Work (reference 3) and Lewis and von Elbe (reference 6) show that at the moment of origin detonation pressures are appreciably higher and can be up to twice as high as the pressures in the stationary wave. However, such momentarily high pressures persist for relatively short distances. Unfortunately, however, there appears to be no information upon the ratio of initial pressure to steady-state pressure.

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In general, the same symbols will be used as those used by Shapiro, Hawthorne, and Edelman. These symbols, together with such additional symbols as necessary to this analysis, are listed below. Dimensions are in the foot-pound-second system. Attention is invited to the general rule that upper case letters are used whenever possible in order to reserve lower case letters for purposes of identification.

A.........cross-sectional area.
c.........speed of sound.
Cp........specific heat at constant pressure.
Cv........specific heat at constant volume.
D.........diameter.
F.........[illegible]
h.........specific enthalpy.
k.........ratio of specific heats.
L.........length of duct.
M.........Mach number.
N.........number of moles.
P.........pressure.
R.........gas constant.
T.........absolute temperature.

U..........entrance velocity.
V..........stream velocity.
W..........mass, mass rate of flow.
X..........distance along duct.
d..........mass density.
δ..........half-angle of divergence.

()a.........refers to air, atmospheric.
()c.........refers to combustion, combustion chamber.
()d.........refers to diffuser.
()e.........refers to exhaust.
()f.........refers to fuel, flame.
()i.........refers to inlet.
()o.........refers to isentropic stagnation condition.
()1,2,3.....refers to sections 1, 2, 3.
()*.........refers to conditions where M = 1.
()'.........refers to conditions relative to observer moving with unburned gas.

3.3 Assumptions.

The following assumptions are made in the interest of simplifying the analysis.

1. The flow is one-dimensional.

2. Changes in stream properties are continuous except in compression shocks or in a detonation wave.

3. The gas is perfect; i.e., it obeys Boyle's and Charles' laws and the specific heats remain constant. ($k = 1.4$)

4. There is no friction.

5. No heat is lost or gained except by combustion.

6. Processes are isentropic except in a shock or detonation wave.

3.4 Continuous Detonative Combustion.

The problem of intermittent detonative combustion can be much simplified by assuming that detonation sets in immediately upon ignition, and that the time interval between explosions is zero. Under such conditions the problem may be analyzed as one of continuous detonative combustion. There is then no back-flow in the diffuser, and the device is very roughly equivalent to a ramjet in which combustion is detonative in character.

for the usual hydrocarbon explosion

$$\frac{To2 - To1}{T1} = \frac{(1-M1^2)^2}{2(k+1)M1^2} = 8 \qquad (1)$$

Solving the foregoing equation for M1 yields two values; one of these represents normal combustion, and the other detonation, as follows:

M1 = 0.18 (Normal combustion)

M1 = 5.54 (Detonation)

From reference 1, equation (60), the following relation is obtained

$$\frac{Po2'}{P1} = \frac{1+kM1^2}{k+1}\left(1 + \frac{k-1(M1^2-1)^2}{2(1+kM1^2)^2}\right)^{\frac{k}{k-1}} \qquad (2)$$

Substituting the detonation value of M1 in equation (2) yields

$$\frac{Po2'}{P1} = 24.82$$

In accordance with reference 1, for the steady detonation wave, M2 = 1. Following the methods of reference 1, and by use of tables contained therein, the following values are obtained:

$$\frac{T2}{T1} = 11.25 \quad \text{and} \quad \frac{P2}{P1} = 17.9$$

From the equations for isentropic flow

$$To2' = T1\,\frac{T2}{T1}\left(\frac{P1}{P2}\,\frac{Po2'}{P1}\right)^{\frac{k-1}{k}} \qquad (3)$$

and

$$T3 = T2\left(\frac{P3}{P2}\right)^{\frac{k-1}{k}} \quad \text{and since } P3 = P1 = Pa$$

$$T3 = T1\,\frac{T2}{T1}\left(\frac{P1}{P2}\right)^{\frac{k-1}{k}} \qquad (4)$$

Combining equations (3) and (4) yields

$$To2'-T3 = T1\left(\frac{T2}{T1}\right)\left(\frac{P1}{P2}\right)^{\frac{k-1}{k}}\left(\left(\frac{Po2'}{P1}\right)^{\frac{k-1}{k}} - 1\right) \qquad (5)$$

Substituting numerical values, and solving equation (5), yields

$$T_{o2'} - T_5 = 2700\ ^{\circ}R.$$

From the equation for specific thrust

$$\frac{F}{W_a} = \left(\frac{2Jc_p(T_{o2'} - T_4)}{g}\right)^{\frac{1}{2}} \qquad (6)$$

is obtained

$$\frac{F}{W_a} = 177 \text{ pounds thrust/pound air/second.}$$

If the fuel used is octene, the stoichiometric fuel/air ratio is

$$\frac{W_f}{W_a} = .0665$$

and the specific fuel consumption is

$$\frac{W_f}{F} = 1.352 \text{ pounds fuel/pound thrust/hour.}$$

It is of interest to compare the foregoing results with the theoretical results obtainable for a stoichiometric mixture of octene and air. The value of octene is

$$H_c = 19{,}150 \text{ Btu/pound.}$$

$$\frac{F_{th}}{W_a} = \left(\frac{2JH_c \; .0665}{g}\right)^{\frac{1}{2}} = 247.3 \text{ pounds thrust/pound air/second.}$$

and the specific fuel consumption is

$$\frac{W_f}{F} = 1.008 \text{ pounds fuel/pound thrust/hour.}$$

From the foregoing it is apparent that continuous detonative combustion is not characterized by very high efficiency. This is not a surprising conclusion, in view of the fact that the efficiency of compression through a compression shock falls off rapidly with increasing Mach number. However, it should be noted that values of specific thrust and specific fuel consumption obtained above are not significantly different from like figures for current turbojets. In the next section an attempt will be made to apply the foregoing methods of analysis to intermittent detonative combustion, and a comparison will be made with the results obtained by Hoffman.

[illegible]

[illegible]

[illegible]

$$\frac{F}{W_a} = [illegible] \qquad (9)$$

is obtained.

$$\frac{F}{W_a} = 477 \text{ pounds thrust/pound air/second.}$$

If the fuel used is kerosene, [illegible]

$$\frac{W_f}{W} = .0449$$

and the specific fuel consumption would be

$$\frac{W_f}{F} = [illegible] \text{ pounds fuel/hour/pound thrust}$$

It is of interest to compare [illegible]

[illegible]

[illegible]

$$= 18,[illegible]$$

$$\frac{F}{W_a} = [illegible] \text{ pounds thrust/pound air/second,}$$

and the specific fuel consumption is

$$\frac{W_f}{F} = [illegible] \text{ pounds fuel/hour/pound thrust}$$

From the foregoing [illegible] This is not a surprising conclusion, in view of the fact that the efficiency of compression through a [illegible] Mach number. However, it should be noted that values of specific thrust and specific fuel consumption obtained above are not significantly different from [illegible] will be made to apply the foregoing methods of analysis to [illegible] combustion, and a comparison will be made with the results obtained [illegible]

3.5 Intermittent Detonative Combustion.

In the preceding section the assumption was made that the time interval between explosions is zero, with the necessary consequence that flow was continuous and no mass other than that of the combustible mixture entered the apparatus. With intermittent operation the last conclusion is no longer valid, because now there exists the possibility of back flow into the diffuser and a consequent increase in the mass accelerated.

As before, however, it will be assumed that detonation sets in immediately upon ignition. Such an assumption is not so arbitrary as may at first appear. It may be remembered from the discussion in section 3.1 that at the instant detonation sets in, and for an appreciable time thereafter, detonation pressures are abnormally high, and may be up to twice the steady-state value. This effect will offset, to some extent, the fact that detonation does not actually commence with ignition, as here assumed.

In order to analyze flow in the diffuser it will be assumed that at the instant exhaust velocity drops to zero pressure distribution is a sine function of axial position, satisfying the following boundary conditions:

At $X = 0$, $P = P1$; at $X = Lc$, $P = 0$; at $X = Lc+Ld$, $P = P1$;

and at $X = Lc - \frac{Po2'}{P1}Ld$, $P = Po2'$.

These conditions represent an asymmetrical sine wave with a maximum equal to P1 at the baffle where fresh mixture enters, a minimum of zero at the spark plug, and another maximum equal to Po2' at such distance from the end of the diffuser as will give a pressure equal to P1 at the diffuser exit. The equation expressing pressure distribution in the diffuser may then be written as follows:

$$P = Po2' \sin 90^{\circ}\frac{P1(X-Lc)}{Po2'} \qquad (7)$$

As $\frac{P1}{Po2'} = .0402$ (From the preceding analysis)

the angle is small for all values of L in the diffuser; therefore the sine can be considered equal to the angle, and equation (7) reduces to

$$P = P1\frac{(L-La)}{La} \tag{8}$$

From the adiabatic gas relation

$$d = d3\left(\frac{P}{P3}\right)^{\frac{1}{k}}$$

and as

$$P3 = P1$$

$$d = d3\left(\frac{P}{P1}\right)^{\frac{1}{k}} \tag{9}$$

Substituting (8) in (9) yields

$$d = d3\left(\frac{L-La}{La}\right)^{\frac{1}{k}} \tag{10}$$

Since the volume of the diffuser can be represented as a simple function of L, the ratio of the mass of residual gas to the mass of air entering the diffuser can be obtained by taking the integral of (10) on L over the diffuser length and dividing this by the product of entering air density and diffuser length, yielding

$$\frac{Mr}{Ma} = \frac{d3}{d1}\frac{(k+1)}{k} \tag{11}$$

or

$$\frac{Mr}{Ma} = \frac{T1}{T3}\frac{(k+1)}{k} \tag{12}$$

after the pressure has become uniform throughout and equal to P1.

If the ratio of the volume of the diffuser to the volume of the combustion chamber is known, the ratio of the total mass accelerated to the mass of fresh mixture may be written. Let the volume ratio above be designated by "Y". Then

$$\frac{Mt}{Me} = 1 + Y\frac{\left(1 + \frac{d3}{d1}\frac{k+1}{k}\right)}{\left(1 + \frac{k+1}{k}\right)}$$

or

$$\frac{Ft}{Wa} = 1 + Y\left\{\frac{1 + \frac{T1}{T2}\frac{k+1}{k}}{1 + \frac{k+1}{k}}\right\} \tag{13}$$

and by substituting for T1 and T2 from the preceding section

$$\frac{Ft}{Wa} = 1 + .50Y \tag{14}$$

It is now necessary to calculate the loss of momentum due to back flow in the diffuser. The mean pressure in the diffuser at the moment back flow begins may be obtained from equation (8), yielding

$$\frac{Pm}{P1} = .5 \tag{15}$$

The specific thrust due to back flow is then

$$-\frac{Fd}{Wd} = \left\{\frac{2JCpT1}{g}\left(1-\left(\frac{Pm}{P1}\right)^{\frac{k-1}{k}}\right)\right\}^{\frac{1}{2}} = 88.9 \tag{16}$$

The ratio of mass in back flow to mass entering the combustion chamber may be derived from equation (11), yielding

$$\frac{Wd}{Wa} = \frac{1}{2k+1} = .304 \tag{17}$$

and the loss of specific thrust due to back flow is

$$\frac{Fd}{Wa} = -\frac{Fd}{Wd}\frac{Wd}{Wa} = 12.9 \tag{18}$$

The net thrust per pound of entering mixture for intermittent detonative combustion can now be computed, if Y is known. Two solutions will be found; the first will be based on a value of Y calculated from the area ratio of the diffuser required to satisfy the flow of the preceding section with a half-angle of divergence of 4°; the second will be based on a value of Y calculated from the dimensions of the diffuser apparatus as described in section 3.1.

<u>First Solution</u>

$Y = 11$

$\frac{Ft}{Wa} = 6.08$

$$\frac{F}{W_a} = \left(\frac{W_t}{W_a}\right)^{\frac{1}{2}} \left(\frac{F}{W_a}\right)_{continuous} - \frac{[illegible]}{[illegible]} \qquad (11)$$

$\frac{F}{W_a}$ = 422 pounds thrust/pound air/second

$\frac{W_f}{F}$ = .566 pounds fuel/pound thrust/hour

<u>Second Solution</u>

Y = 66

$\frac{W_t}{W_a}$ = 33.2

$\frac{F}{W_a}$ = 1067 pounds thrust/pound air/second

$\frac{W_f}{F}$ = .281 pounds fuel/pound thrust/hour

The second solution above is obviously not realistic. It is of interest to compare the first solution with the specific thrust and fuel consumption that Hoffman obtained experimentally for his apparatus. To make the comparison of value Hoffman's data will be corrected for the difference in mass between oxygen, which he used, and air, on which all the foregoing analyses are based.

The mass ratio of air to oxygen is

$\frac{W_a}{W_o}$ = 4.2

and the corrected specific thrust

$$\frac{F}{W_a} = \frac{F(W_a/W_o)^{\frac{1}{2}}}{[illegible]} = 289 \text{ pounds thrust/pound air/second}$$

The corrected specific fuel consumption

$$\frac{W_f}{F} = \frac{[illegible]}{F(W_a/W_o)^{\frac{1}{2}}} = .207 \text{ pounds fuel/pound thrust/hour}$$

The analytic specific thrust and specific fuel consumption compared with the corrected experimental specific thrust and specific fuel consumption show a consistent discrepancy; i.e., the ratio of specific thrusts is .686 and the reciprocal ratio of the specific fuel consumptions is .706.

In view of the basic assumptions the analysis here presented appears to agree quite well with experimental data. A more detailed analysis, taking into account changes in specific heats with temperature, effects of friction, and heat efficiency will undoubtedly yield results in closer agreement with experimental data. Perhaps of even greater importance would be an analysis of flow in the diffuser based on acoustic analyses rather than the simplified assumptions here made.

4. EQUIPMENT, TESTS, AND RESULTS

4.1 Introduction.

The results of Hoffman's experiments, and the analysis preceding, indicate that there are two basic problems in the development of a practical thermal jet based on the principle of intermittent detonative combustion. The first and foremost problem is that of finding a common fuel which will detonate in air, or a means of inducing detonation in combustible mixtures which do not ordinarily detonate. The second problem, based on the assumption that the first problem is subject to solution, has to do with the question of whether detonation will occur when the air supply is ram air; i.e., if detonative mixtures under pressures easily obtainable through ram recovery will detonate in tubes open at both ends. The tests following are an attempt to find the answer to these two problems. As only qualitative results were desired, no measurements of thrust or fuel consumption were taken.

4.2 Oxygen-Gasoline Tests.

Fig. 2 is a diagrammatic sketch of the apparatus used. Essentially it consists of a combustion chamber in the form of a tube with a spark plug at one end and a baffle at the other. A hole in the baffle gives access to a mixing chamber, and oxygen and gasoline lines feed into the

mixing chamber at its far end. The gasoline and oxygen inlets to the mixing chamber are so arranged that oxygen flow will atomize the gasoline.

At low mixture flow rates ordinary combustion as in a blow-torch was obtained, and after initial ignition combustion was continuous. As the flow rate was increased an oscillatory[1] combustion of exceedingly high frequency manifested itself, evidenced by an ear-splitting whistle of high pitch and great intensity. Further increase of flow rate resulted in intermittent[1] detonative[2] combustion. This test was conducted as a rough check of Hoffmann's report, and its aim was primarily to enable the author to recognize intermittent detonative combustion when encountered subsequently.

4.2 Air-Acetylene Tests.

Fig. 8 is a diagrammatic sketch of the apparatus used. Essentially it is the same as the apparatus described in the preceding section, with the exception that the mixing chamber was modified as shown. An ordinary household vacuum cleaner was used as a source of air, and flow was varied by restricting the entrance area.

The results obtained in these tests were substantially identical with those obtained in the oxygen-gasoline tests, except that the frequency of oscillatory combustion was much lower, as were the reactive forces. Combustion tubes of different diameter were tried as well as different flow rates in a tube of fixed diameter, from which it was

[1]By "oscillatory" combustion is meant combustion in which the flame front oscillates at some fixed frequency without ever wholly dying out, as in an ordinary pulsejet; and continuous ignition is unnecessary. By "intermittent" combustion is meant combustion which completely ceases once during each cycle and continuous or cyclic ignition is required.

[2]No apparatus for determining the existence of detonation was available; however, the sharp character of the ensuing explosions and the large reactive forces observed are considered evidence of detonation.

determined that the character of combustion appears to be a function of Reynold's number, changing from ordinary to oscillatory to intermittent with increasing Reynold's number.

The results of these tests indicate that the answer to the second problem outlined in the introductory section is affirmative at least in so far as a mixture of air and acetylene is concerned.

4.4 Air-Gasoline Tests.

Fig. 6 is a diagrammatic sketch of the apparatus used. Essentially it is the same apparatus described in section 4.2 except that air supplied by an ordinary household vacuum cleaner was used instead of oxygen. Note, however, that the mixing chamber is larger in order to permit extensive vaporization of the fuel.

At low air velocities ordinary combustion as in a blow-torch was obtained. At high air velocities, and after the apparatus had become well heated so that vaporization was rapid and complete, the combustion was oscillatory in character. It was observed that the frequency in oscillatory combustion increased steadily as the fuel-air ratio was reduced until the lower limit for combustion was reached and combustion ceased. This phenomenon, for which the author has no adequate explanation at this time, was duplicated several times. Intermittent combustion could not be obtained under any circumstances, nor was there any evidence of detonation.

4.5 Air-Ether Tests.

These tests were conducted in the same manner and with the same apparatus as those described in the preceding section. The results were substantially identical, including increase of frequency with decreasing fuel-air ratio, except that ether vaporized more readily so that oscillatory combustion was obtained immediately with cold apparatus.

4.6 Air-Ether-Gasoline Tests.

These tests were conducted in the same manner and with the same apparatus as those described in section 4.4, with the exception that a mixture of ether and gasoline in various proportions was used in place of gasoline alone. The results obtained were substantially identical with those of the preceding two sections. The time necessary for the apparatus to reach a temperature at which oscillatory combustion would take place was a function of the proportion of ether to gasoline in the mixture.

4.7 Air-Oxygen-Gasoline Tests.

These tests were conducted in the same manner and with the same apparatus as those described in section 4.4, except that an auxiliary oxygen line was connected to the mixing chamber in order to enrich the air. Only moderate enrichment was tried, and the results were not materially different from those obtained with un-enriched air.

4.8 Pulsejet Tests.

In these tests a model pulsejet was provided with a second spark-plug at approximately the mid-point of the device. The arrangement had no effect at all on the normal operation of the pulsejet irrespective of fuel-air ratio.

4.9 General Remarks.

Early in the course of the tests conducted above it became apparent that the problem of bringing fuel and oxidizer into intimate contact was a major one. A large number of different mixing chambers was tried. In general, all had the drawback of permitting flash-back and combustion within the mixing chamber under certain conditions of flow, except where detonation obtained.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions.

Hoffman has demonstrated, and two of the tests here conducted corroborate, that the principle of intermittent detonative combustion can be successfully applied to thermal jet propulsion. Analysis of intermittent detonative combustion indicates that a device based on this principle can be constructed with the promise of yielding a high specific thrust at low specific fuel consumption; moreover, such a device would have the virtues of simple design and construction, low weight, and freedom from moving parts.

From the results of the tests described in the preceding section it would appear that intermittent detonative combustion cannot be obtained with the use of gasoline or ether and air mixtures. However, Breton and Lafitte obtained detonation in stagnant ether-air mixtures; and Dixon succeeded in obtaining detonation in stagnant alcohol-air mixtures. It is therefore not unreasonable to expect that further research will lead to the discovery of some common and readily available fuel which can be used with air in an intermittent detonative combustion thermal jet.

5.2 Recommendations.

The foregoing analysis and tests show the need for basic knowledge of, research in, and analytic treatment of a number of factors. These factors are briefly outlined in the following paragraphs.

1. Tests must be conducted in order to ascertain the effect of Reynold's number on the incidence and progress of detonation. Heretofore all investigation of the phenomenon of detonation has been concerned with stagnant mixtures. The effect of turbulence on ordinary combustion has received some attention; however, detonation in turbulent

4. Conclusions and Recommendations

4.1 Conclusions.

[illegible]

From the results of the tests reported in the preceding pages it would appear that [illegible] [illegible] fuel which can be used with air in an intermittent detonation [illegible] thermal jet.

4.2 Recommendations.

The foregoing analysis and tests show the need for more knowledge of, [illegible], and analytic treatment of a number of factors. These factors are briefly outlined in the following paragraphs.

1. Tests must be conducted in order to ascertain the effect of Reynold's number on the frequency and [illegible] of detonation. Heretofore all investigation of the phenomena of detonation has been conducted with [illegible] mixtures. The effect of [illegible] [illegible]

mixtures has not been investigated except in the case of internal combustion engines.

2. In connection with the preceding recommendation, different fuels in air mixtures need to be investigated to determine their detonation characteristics in turbulent flow, with a particular view to finding a common fuel or combination of common fuels which will detonate readily in air. A fuel consisting of a solution of acetylene in gasoline under pressure is a suggestion.

3. Investigation should be made of the possibility of initiating detonation in mixtures which do not detonate readily by auxiliary means; as by the use of auxiliary supply lines located so as to put a fuel-oxygen mixture in front of the fuel-air mixture, or by use of a very high voltage discharge at the spark-plug.

4. Flow in the diffuser under conditions of intermittent detonative combustion needs to be analyzed at greater length and in greater detail than was done here. The problem is probably one of vibration, and the effects of resonance are undoubtedly important.

5. The feasibility of improving flow in the diffuser by means of reed or other valves at the diffuser entrance should be investigated. The use of valves is objectionable from the point of view of mechanical endurance, as is the case in the pulsejet; however, in the intermittent detonative combustion device these valves would probably not be subjected to the high impact loads present in the pulsejet.

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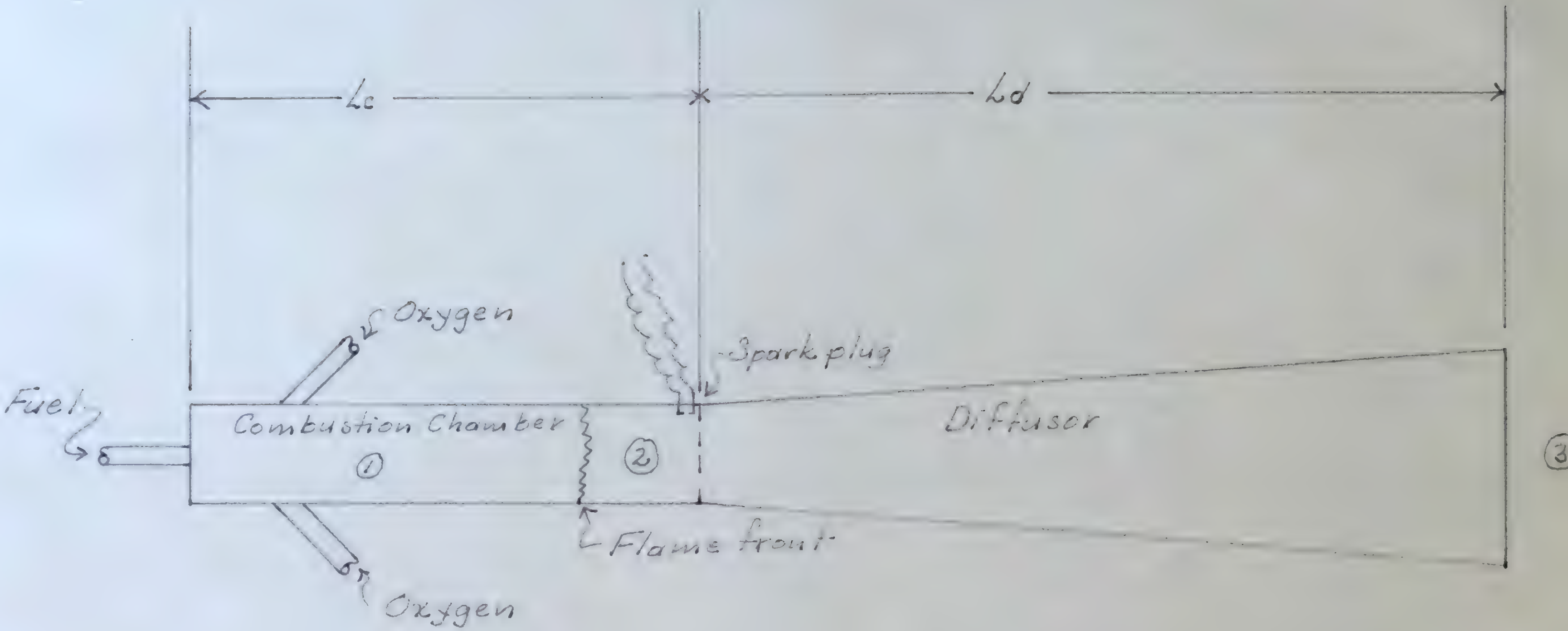

Fig. 1 Hoffman's Apparatus

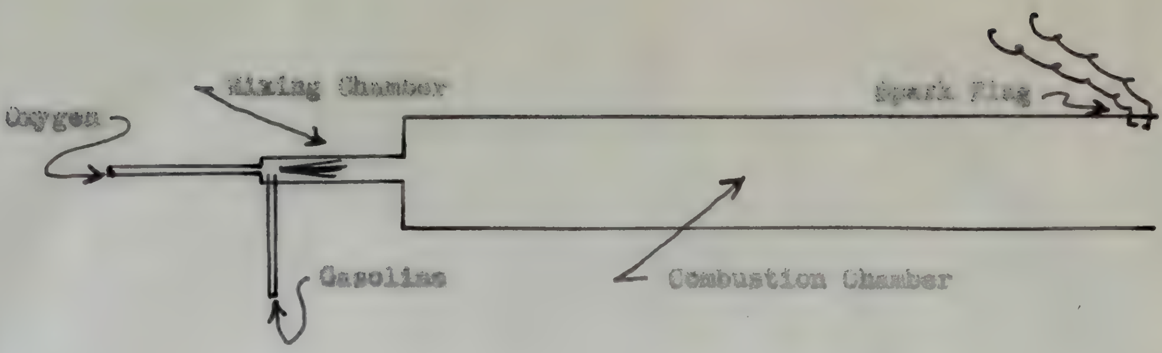

Fig. 2 Oxygen-Gasoline Test Apparatus

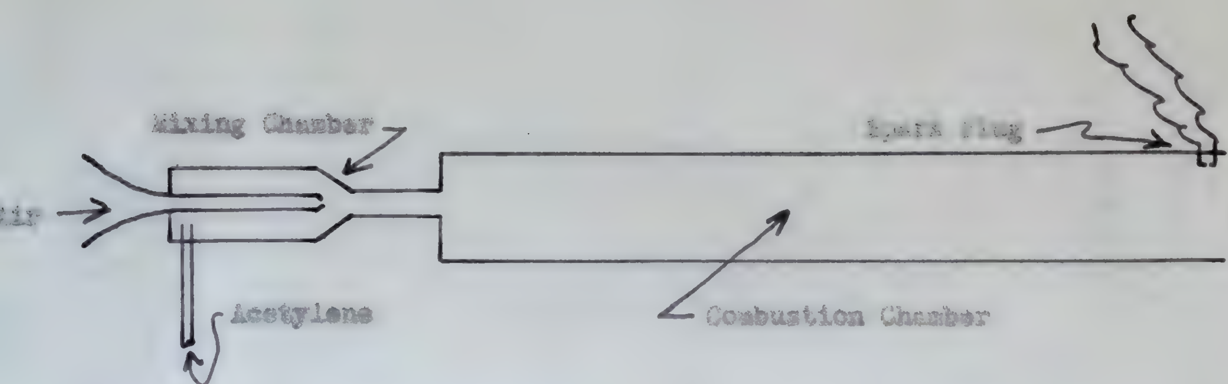

Fig. 3 Air-Acetylene Test Apparatus

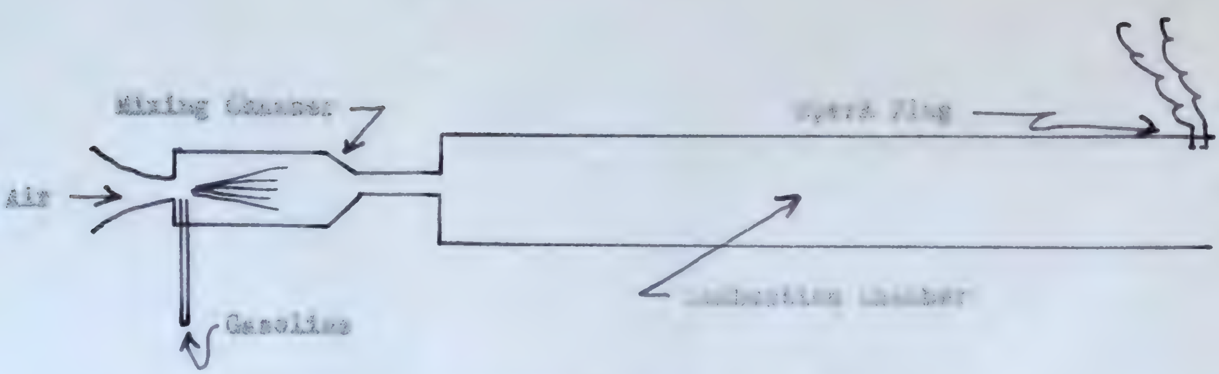

Fig. 4 Air-Gasoline Test Apparatus